The logic of knowledge bases: A review

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A knowledge-based system (KBS) contains (by definition) an explicitly codified body of knowledge, which causally determines its behavior. Hence, at a coarse-grained level of abstraction, KBSs can be characterized in terms of two components: (1) a knowledge base, encoding the knowledge embodied by the system, and (2) a reasoning engine, which is able to query the knowledge base, infer or acquire knowledge from external sources, and add new knowledge to the knowledge base. Levesque and Lakemeyer's *The Logic of Knowledge Bases* deals with the "internal logic" of a KBS: It provides a formal account of the interaction between a reasoning engine and a knowledge base. Clearly, this analysis is not the same as providing a formal account of the behavior of a KBS as a whole. A knowledge-level account of a KBS (that is, a competence-centered, implementation-independent description of a system), such as Clancey's (1985) analysis of first-generation rule-based systems, focuses on the task-centered competence of the system; that is, it addresses issues such as what kind of problems the KBS is designed to tackle, what reasoning methods it uses, and what knowledge it requires. In contrast with task-centered analyses, Levesque and Lakemeyer focus on the competence of the knowledge base rather than that of the whole system. Hence, their notion of competence is a task-independent one: It is the "abstract state of knowledge" (p. 49) denoted by the contents (implicit or explicit) of a knowledge base at any particular time in its life cycle. This is an interesting assumption, which the "proceduralists" in the AI community might object to: According to the procedural viewpoint of knowledge representation, the knowledge modeled in an application, its representation, and the associated knowledge-retrieval mechanisms have to be engineered as a function of the task in hand; for example, see Bylander and Chandrasekaran's (1988) discussion on the interaction hypothesis. As a result, they would argue, it is not possible to discuss the knowledge of a system independently of the task context in which the system is meant to operate. I won't go into too many details here because a detailed discussion of the declarative versus the procedural argument is well beyond the scope of this review. The important point to make is that Levesque and Lakemeyer's approach is situated in a precise AI research paradigm, which considers knowledge bases as declaratively specified, task-independent representations of knowledge.

The Logic of Knowledge Bases, Hector J. Levesque and Gerhard Lakemeyer, Cambridge, Massachusetts, The MIT Press, 282 pp., $45.00, ISBN 0-262-12232-4.

Starting from such a declarativist standpoint, Levesque and Lakemeyer view a knowledge base as an epistemic agent, and they set out to specify formally what knowledge can be attributed to such a system. To talk about the epistemic state of a knowledge base, Levesque and Lakemeyer introduce an extra logical symbol, *K*, to be able to distinguish what is known from what is true. At this point, a reader might wonder why the authors can't simply stick to classical first-order logic and describe what is true about the world? The reason, argue Levesque and Lakemeyer, has to do with incomplete knowledge. If a system has complete knowledge, then of course there is no difference between what is known and what is true: The two sets coincide. However, when a system has incomplete knowledge, things become more complicated. For example, a system might know that Mary has a teacher without knowing the identity of such an individual. Explicitly distinguishing what is true from what is known makes it possible for a system to deal correctly with these scenarios.

The introduction of the epistemic operator, *K*, requires the adoption of a possible world semantics for the interaction language (the language used by a reasoning engine to interact with a knowledge base at the knowledge level). In short, the abstract state of the knowledge of an agent (that is, its epistemic state) can be characterized as the collection of all possible worlds that are consistent with the knowledge held by the agent. If the knowledge of the agent is complete, then the epistemic state contains only one world. A nice feature of Levesque and Lakemeyer's treatment of epistemic logic is that in contrast to many other treatments of modalities, the discussion is reasonably easy to follow for people who are not experts in the field. This is the result of two main features of this analysis: First, the authors introduce some simplifying assumptions, such as the use of standard names to identify individuals in the universe of discourse, that do not affect the substance and the general applicability of the proposed models. Second, although the proposed language extends first-order logic with an epistemic operator, Levesque and Lakemeyer succeed in reconciling their analysis within a standard first-order–logic framework. Thus, the reader is not forced into learning a new syntax, and the underlying model theory is a "reasonably conservative" extension of standard model theory for first-order logic. More importantly, the previous statement can be given a strong interpretation because the representation theorem, discussed in chapter 7, shows that for finite knowledge bases both Tell and Ask operations (see later for more details on the Tell and Ask protocol) can always be realized using objective sentences, that is, sentences expressed in standard first-order logic. The ability to reduce formal treatments of modalities to standard first-order logic is an important result, given that standard first-order logic is far better understood

and computationally tractable than modal logics. Having said so, one slightly confusing aspect of Levesque and Lakemeyer's analysis is that although Levesque and Lakemeyer talk about modeling knowledge, they are actually modeling beliefs. For those used to "classical" theories of knowledge, this is slightly confusing because in Levesque and Lakemeyer's treatment, an agent might know something that is not true, but in many other treatments, everything known must be true (that is, the real world is always one of the possible worlds available to an epistemic agent). This is a bit disconcerting at first, but eventually the reader gets used to it; that is, he/she eventually rests assured that it is Levesque and Lakemeyer's epistemic agents who might be affected by solipsism rather than he or she.

The problem of how to handle formally and effectively incomplete knowledge is one of the two main goals of the book. The other has to do with precisely characterizing the behavior of a knowledge base at the knowledge level. The perspective of a knowledge-level view of intelligent systems was first proposed by Allen Newell in 1981 and has since informed much work in knowledge representation. In contrast with Newell's goal-oriented view of a knowledge-level system as an epistemic agent, as already mentioned, Levesque and Lakemeyer are not concerned with goal-driven behavior. For them, a knowledge base is essentially a task-independent body of knowledge to be interacted with by means of two basic operations: Tell, to add new knowledge, and Ask, to find out what the system knows or what is true about the world. Chapter 5 in the book formally specifies Tell and Ask as operations that take as arguments a sentence and an epistemic state and return either an element in the set {yes, no} (Ask) or a new epistemic state (Tell).

The first half of the book covers the basics, and the second half shows applications of the framework to nonmonotonic reasoning, tractable reasoning, and reasoning about actions. I won't go into too many details here, but essentially Levesque and Lakemeyer show how their framework can be used to reconstruct approaches such as Robert Moore's epistemic logic and John McCarthy's situation calculus. Of particular interest are chapters 12 and 13, which discuss a semantic approach to logical omniscience. A standard problem in knowledge representation is the trade-off between expressivity and computational efficiency. Most solutions err either on the side of expressivity (that is, you might wait a long time for an answer) or efficiency (that is, you are guaranteed an answer, but there is a lot that you are prevented from representing). Levesque and Lakemeyer show that it is possible to distinguish between explicit and implicit beliefs by providing a four-valued semantics (in addition to standard true and false truth assignments, sentences can now be either true and false or neither true nor false). The distinction between implicit and explicit beliefs enables very efficient decision procedures for explicit beliefs in the context of a very expressible language.

Thus, what is the general assessment of this book, and what audience is the book relevant to? The answer to the first question is quite easy. This is clearly a very good book, which provides a powerful, formal, and detailed (but reasonably easy-to-follow) logical treatment of some of the thorniest issues in knowledge representation: incomplete knowledge, nonmonotonic reasoning, reasoning about actions, and logical omniscience. The answer to the second question is a bit more complicated. The book is definitely going to be required material for anybody interested in formal knowledge representation or in formal theories of knowledge. However, what about the wider world of knowledge-based systems? After all, one would expect a book with the words *knowledge base* in the title to be of interest to the wider community of researchers and practitioners in the area of knowledge-based systems. In addition, it would be nice if such interest was not going to be driven purely by intellectual curiosity but also by the possibility of applying these results to the engineering of real systems in real contexts. Unfortunately, no attempt is made in the book to link the analysis either to concrete applications or to research in task-performing knowledge-based systems, for example, the work by Bill Clancey, Mark Stefik, and Balaknishman Chandrasekaran in the United States and by Bob Wielinga and others in Europe (Bylander and Chandrasekaran 1980; Clancey 1985; Fensel et al. 1999; Stefik 1995; Schreiber et al. 2000). Au contraire, the reader gets the feeling that the authors are actually not that interested in applications of knowledge representation technology: The examples in the book tend to be of the "Tweety is a bird" variety, and none of the 143 references seems to be related to some application.

In conclusion, this is an excellent book, which is very much grounded in the AI tradition of symbolic representation of knowledge. Anybody interested in formal representations of knowledge and epistemic agents should definitely read this text. However, those readers who are primarily interested in knowledge-based systems viewed as task-performing agents should definitely note that the word *systems* does not follow the words *knowledge base* in the title of the book. This omission is indeed a significant one!

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